AFRL-SR-BL-TR-98-

0475

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED
Final 01 Jan 95 to 31 Mar 98

4. TITLE AND SUBTITLE
Single Electronics

5. FUNDING NUMBERS
61102F
2305/GS

6. AUTHOR(S)
Professor Likharev

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
State University of New York
Melville Library, W5510
Stony Brook Ny 11794-3366

19980615 037

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NE
110 Duncan Ave Room B115
Bolling AFB DC 20332-8050

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
F49620-95-1-0044

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVAL FOR PUBLIC RELEASED: DISTRIBUTION UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

During the past decade, single-electronics (for general reviews, see Refs. 1-3) has turned into a major field of physical and applied electronics. Preliminary studies of possible applications of single-electron devices (1,4,5) indicated that they might yield a completely new generation of both digital and analog devices with unparalleled performance, most notably extremely dense digital circuits. However, many issues before the beginning of this work these expectations have not been confirmed by detailed, quantitative analyses. In 1991, a collaboration of three research groups at Stony Brook, headed b Professors Dmitri averin, Konstantin Likharev and James Lukens, began an AFOSR-supported project in the field of single-electronics. During the few first years of this work, a solid technological, experimental and theoretical base for single-electronics was established at Stony Brook, and many interesting results have been obtained. Since January 1995, this research has been supported under the current grant.

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18

DTIC QUALITY INSPECTED 3

SINGLE-ELECTRONICS

AFOSR Grant # F49620-95-1-0044

Final Technical Report

Principal Investigator: Prof. Konstantin K. Likharev

Co-P.I.s: Prof. Dmitri V. Averin
Prof. James E. Lukens

Address: Department of Physics and Astronomy
State University of New York at Stony Brook
Stony Brook, NY 11794-3800

Phone: 516-632-8159
Fax: 516-632-8774
e-mail: klikharev@ccmail.sunysb.edu

Grantee: Research Foundation
State University of New York at Stony Brook
Stony Brook, NY 11794

Project Period: January 1, 1995 - March 31, 1998

May 1998

PS 86

Executive Summary

During the past decade, single-electronics (for general reviews, see Refs. 1-3) has turned into a major field of physical and applied electronics. Preliminary studies of possible applications of single-electron devices [1, 4, 5] indicated that they might yield a completely new generation of both digital and analog devices with unparalleled performance, most notably extremely dense digital circuits. However, many issues before the beginning of this work these expectations have not been confirmed by detailed, quantitative analyses.

In 1991, a collaboration of three research groups at Stony Brook, headed by Professors Dmitri Averin, Konstantin Likharev and James Lukens, began an AFOSR-supported project in the field of single-electronics. During the few first years of this work, a solid technological, experimental and theoretical base for single-electronics was established at Stony Brook, and many interesting results have been obtained. Since January 1995, this research has been supported under the current grant.

In the course of this project, we have addressed several key issues of fundamental and applied single-electronics. The highlights of our achievements include:

(a) The first experimental observation of upper band energy structure at single-Cooper-pair tunneling;

(b) A thorough analysis of several analog and digital single-electron devices including the first complete SET logic family and the first reversible single-electron logic;

(c) The first quantitative comparison between experimental data and numerical simulation of a multi-junction single-electron device.

Several important issues of single-electronics (e.g., the relaxation of random background charge, decoherence of macroscopic quantum charge states, quasi-continuous transfer of charge in nanostructures with hopping conductance, etc.) still remain open and require further experimental and theoretical studies. Some of them will be addressed in our further work. We believe, however, that the completed project has been an important step toward thorough understanding and practical applications of single-electron devices.

Major Results

A. Bloch Transistors [6]

Participants[1]: D.J. Flees*, S. Han, J. Lukens

The single-Cooper-pair version of single-electron transistor (often known as Bloch transistor) has significant advantages for many device applications. For example, it can have a low output impedance, permitting it to drive long lines at high frequencies. This mode is achieved via modulation of the transistor's critical current by the gate voltage. In this mode, the device has a capacitive input in some tens aF and an output impedance which can be reduced to say 50 W by putting a resistive shunt across the output terminals. It has also been predicted that Bloch transistors can be excited to upper energy bands, with the band index corresponding roughly to the number of extra Cooper pairs in the island connecting the Josephson junctions.

We have carried out the first clean (i.e., not contaminated by external noise) measurements of the switching currents in $Al/AlO_X/Al$ Bloch transistors with large ratio of Josephson coupling energy E_J to elementary charging energy E_C ($E_J/E_C > 5$). A key to this achievement was the development of highly efficient, compact microwave filters with cutoff frequency below 100 kHz, which provide a microwave attenuation of over 70 db for all 68 leads connecting the sample chip with room temperature electronics.

As a result, we have obtained direct evidence of the first excited energy band and measured the energy gap separating it from the ground energy band, as a function of gate induced charge. This was accomplished by irradiating the transistor with microwaves of various frequencies. When the photon frequency becomes larger than the energy gap, the transistor is pumped to the excited band providing lower critical current. The results provide excellent, quantitative confirmation of a very important aspect of the Bloch transistor theory.

B. Superconductor Single-Electron Transistors [7, 8]

Participants: D. Averin, A. Korotkov

Even in the absence of Cooper-pair tunneling, superconductivity of electrodes and/or island may change the signal and noise properties of single-electron transistors considerably. We have analyzed this problem for both SISIS and NISIN structures.

An important process which affects the sensitivity of the transistor as an electrometer is quasiparticle cotunneling. The BCS singularity in the density of states of

---

[1]Stars denote students

the superconducting electrodes of the transistor has two qualitative effects on the cotunneling current. The first one is the change of voltage dependence of the current at the onset of tunneling to linear (from cubic in the normal-metal transistors). The second, and more important, effect is the appearance of the finite lifetime of the charge states of the transistor right at the threshold of classical tunneling. As a result, the current flow through the transistor becomes virtually equivalent to the resonant tunneling through a single quantum state. In particular, the differential conductance at resonance is universal and equal to e^2/h. This analogy with resonant tunneling is important in determining the ultimate sensitivity of the SET electrometer limited by quantum fluctuations of charge on the transistor. The experiments carried out by the group of J. Pekola (University of Jyväskylä, Finland) have shown a quantitative agreement with the theory.

From the point of view of electrometry applications, our analysis has shown that the noise-limited charge sensitivity of these devices can be considerably higher than that of their normal-metal counterparts.

C. 1D Arrays: Single-Electron Solitons and Shot Noise [9, 10]

Participants: K. Matsuoka*, K. Likharev

One-dimensional array of small islands separated with tunnel junctions is one of the major components of several single-electron devices. We have analyzed two key properties of such arrays. First, we have calculated the shape and energy of single-electron solitons in 1D arrays without the ground plane, which are used in most experiments, but had been completely ignored by theorists. The analysis has shown that regardless of the junction shape and cross-section, the soliton profile and parameters may be well described by a simple formula. This formula, in particular, describes a natural crossover between the intrinsic field of the soliton and its unscreened Coulomb potential at large distances.

Second, we have studied the intensity of non-equilibrium fluctuations ("shot noise") of current flowing in 1D arrays, both with and without the ground plane. This issue is of key importance for some applications, since the shot noise intensity in intimately related to the discreteness of charge transfer along the array. Namely, the charge transfer may be considered quasi-continuous only if the spectral density $S_I(\omega)$ of shot noise is much lower that the value $2eI$ (the "Schottky formula"). We have found that increase of the average current I leads to a universal crossover of $S_I(0)$ from $2eI$ to $2eI/N$, where N is the number of junctions in the array, regardless of geometry, background charge distribution, and other parameters. These parameters, however, may have a substantial impact on the value of dc current at which the crossover is reached. We have found this dependence for several cases including a very important limit of completely random background charges.

D. Single-Electron Current Standards [11, 12]

Participants: L. Fonseca*, A. Korotkov, K. Likharev

One of the most important potential applications of 1D single-electron arrays is fundamental standards of dc current. We have used our program SENECA (developed during the earlier project) for a detailed analysis of various fundamental standards of dc current, based on multi-junction arrays of single-electron junctions. The list of the devices included single-electron pump, single-electron turnstile, and an original pump-turnstile hybrid. Several possible waveforms of the rf drive voltage have been considered.

The analysis has shown that characteristics of existing dc current standards can be improved substantially if an optimized waveform and/or optimal values of junction resistances are used. For example, a 5-junction pump with a realistic junction size can have relative error as low as 10^{-13} (at 100 mK and 10 MHz).

E. Single-Electron-Transistor Logic [13-15]

Participants: R. Chen*, A. Korotkov, K. Likharev

The current interest to single-electron devices is substantially based on the hope of their prospective applications in ultradense digital integrated circuits. In the course of this project we have addressed both main directions of the development of these circuits: single-electron-transistor logic and single-electron logic.

In the former direction, we have suggested the first functionally complete set of complementary logic gates based on capacitively-coupled single-electron transistors. The analysis has shown that all the gates of the family can have a reasonable maximum temperature $T_{\max}$~$0.025e^2/Ck_B$ (where C is the minimum tunnel junction capacitance available in a particular technology), and relatively broad parameter margins at T~$T_{\max}/2$. Moreover, if the standard. 2-junction transistors are replaced for 1D multi-junction arrays, $T_{\max}$ may be considerably higher (e.g., 0.07 e^2/Ck_B for 5-junction arrays).

Our study has indicated, however, three major problems faced by single-electron-transistor logics:

(a) very tight fabrication requirements (~1 nm for 300 K operation);
(b) threshold shifts by random offset charges; and
(c) high static power dissipation (~100 W/cm^2 at density of 10^{11} bits/cm^2 and operation temperature of 20K).

F. Single-Electron Logics [17, 18]

Participants: A. Korotkov, T. Usuki[2], K. Likharev

The last drawback of SET logic circuits which was mentioned above may be circumvented using logic circuits of the SEL type, which present digital bits by single electrons through the whole system and do not have noticeable static power consumption. We have suggested and analyzed two new families of ac-electric-field-driven SEL devices:

(a) irreversible devices based on the generation of electron-hole pairs in short arrays of tunnel junctions [17], and
(b) "single-electron parametrons" which may be used as reversible devices as well [18].

Analysis has shown that margins for some parameters (notably, the driving field amplitude) are considerably broader for the latter devices. Besides that, the single-electron parametron is presumably the first realistic reversible device using a discrete degree of freedom for coding binary information. [As a by-product of this work, we have found that the widely advertised "Quantum Cellular Automata" based on ground state evolution cannot work at any appreciable speed, because of trapping in intermediate metastable states.]

Our analysis of single-electron logic devices has shown that they still suffer from the first two drawbacks listed in Sec. E above. Recently we have, however, suggested [20] hybrid SET/FET devices which may circumvent both problems.

G. Quantitative Analysis of a Single-Electron Trap [16]

Participants: K. Matsuoka*, P. Dresselhaus, S. Han, L. Ji, K. Likharev, J. Lukens

For the reliable forecast of the performance of future single-electron devices, the ability to carry out their reliable quantitative analysis is certainly of a key importance. We are not aware, however, of any previous attempt to quantitatively compare experimental data for a particular device with results of theoretical analysis including geometrical modeling.

In our earlier AFOSR-supported project we designed, fabricated, and tested several versions of single-electron traps. Such a system consists of an aluminum thin-film island, connected to an external nanowire by a 1D array of a few tunnel junctions, and an electrometer using a single-electron transistor. Externally applied voltage of a few

[2]Visitor from Fujitsi

millivolts to the nanowire leads to injection/extraction of an additional electron into/from the trap through the array. Experiments have shown that the system can really trap a single electron and keep it for a long time (at least 12 hours at T<100 mK).

At this stage, experimental results were compared with results of its numerical modeling and simulation using our own programs MOSES and SENECA, as well as MIT's program FASTCAP which had been substantially modified and expanded at Stony Brook. The analysis indicates reasonable quantitative agreement between theory and experiment for those trap characteristics which are not affected by random offset charges. The observed differences (from a few per cent to a few tens per cent) can be readily explained by the uncertainty in the real geometry of the experimental nanostructures.

H. New Method of Fluctuation Analysis of Single-Electron Systems [20]

Participants: A. Korotkov, K. Likharev

One more methodological work [20] was the development of a new method of analysis of noise in single-electron devices, based on an approach similar to the Boltzmann-Langevin method in the theory of diffusive conductors. The new method has been shown to be mathematically equivalent to the previous approach based on the master equations, but it allows to carry out analyses of some problems in a more straightforward way.

J. Reviews

During the period of our project, we have published several review papers on various aspects of single-electronics [21-23].

References

1. K.K. Likharev, "Correlated Discrete Transfer of Single Electrons in Ultrasmall Tunnel Junctions", IBM J. Res. Devel. **32**, 144 (1988).

2. D.V. Averin and K.K. Likharev, "Single-Electronics", in: *Mesoscopic Phenomena in Solids*, ed. by B. Altshuler, P. Lee, and R. Webb (Elsevier, Amsterdam, 1991), p. 173.

3. *Single Charge Tunneling*, ed. by H. Grabert and M. Devoret (Plenum, New York, 1992).

4. K. K. Likharev, "Single-Electron Transistors: Electrostatic Analogs of DC SQUIDs", IEEE Trans. Magn. **23**, 1142 (1987).

5. D.V. Averin and K.K. Likharev, "Possible Applications of the Single Charge Tunneling", in: *Single Charge Tunneling,* ed. by H. Grabert and M.H. Devoret (Plenum, New York, 1992), p. 311.

6. D.J. Flees, S. Han, and J.E. Lukens, "Interband Transitions and Band Gap Measurements in Bloch Transistors", Phys. Rev. Lett. **78**, 4817 (1997).

7. A.N. Korotkov, "Charge Sensitivity of Superconducting Single-Electron Transistor", Appl. Phys. Lett. **69**, 2593 (1996); A. N. Korotkov, "Superconducting single-electron transistor as an electrometer", in: *Quantum Devices and Circuits*, edited by K. Ismail, S. Bandyopadhyay, and J. P. Lerburton (World Scientific, Singapore, 1997), pp. 211-216.

8. D.V. Averin, A.N. Korotkov, A.J. Manninen, and J.P. Pekola, "Resonant Tunneling through a Macroscopic Charge State in a Superconductor Single Electron Transistor", Phys. Rev. Lett. **78**, 4821 (1997).

9. K.K. Likharev and K.A. Matsuoka, "Electron-electron Interaction in Linear Arrays of Small Tunnel Junctions", Appl. Phys. Lett. **67**, 3037 (1995).

10. K.A. Matsuoka and K.K. Likharev, "Shot Noise of Single-Electron Tunneling in One-Dimensional Arrays", accepted for publication in Phys. Rev. B (June 15, 1998).

11. L.R.C. Fonseca, A.N. Korotkov, and K.K. Likharev, "A Numerical Study of the Accuracy of Single-Electron Current Standards", J. Appl. Phys. **79**, 9155 (1996).

12. L.R.C. Fonseca, A.N. Korotkov, and K.K. Likharev, "Accuracy of the Single-electron Pump with an Optimized Step-like RF Drive Waveform", Appl. Phys. Lett. **69**, 1858 (1996).

13. A.N. Korotkov, R.H. Chen, and K.K. Likharev, "Possible Performance of Capacitively Coupled Single-electron Transistors in Digital Circuits", J. Appl. Phys. **78**, 2520 (1995).

14. R.C. Chen, A.N. Korotkov, and K.K. Likharev, "Single-electron Transistor Logic", Appl. Phys. Lett. **68**, 1954 (1996).

15. R.H. Chen and K.K. Likharev, "Multi-Junction Single-Electron Transistors for Digital Applications", Appl. Phys. Lett. **72**, 61 (1998).

16. K.A. Matsuoka, K.K. Likharev, P. Dresselhaus, L. Ji, S. Han, and J.E. Lukens, "Single Electron Traps: A Quantitative Comparison of Theory and Experiment", J. Appl. Phys. **81**, 2269 (1997).

17. A.N. Korotkov, "Wireless Single-electron Logic Biased by AC Electric Field", Appl. Phys. Lett. **67**, 2412 (1995).

18. K.K. Likharev and A.N. Korotkov, "Single-electron Parametron: Reversible Computation in a Discrete-state System", Science **273**, 763 (1996).

19. K.K. Likharev and A.N. Korotkov, "Ultradense Hybrid SET/FET Dynamic RAM: Feasibility of Background-Charge-Independent Room-Temperature Single-Electron Digital Circuits", in: *Proc. ISDRS'95* (Charlottesville, VA, Dec. 1995), pp. 355-358; VLSI Design (Amsterdam) **3**, 201 (1997).

20. A.N. Korotkov, "Langevin Approach to the Shot Noise Calculation at Single-Electron Tunneling", submitted to Europhys. Lett. (Jan. 1998).

21. K. Likharev, "Physics and Possible Applications of Single-Electron Devices", FED Journal **6**, Suppl. 1, pp. 5-14 (1995).

22. A. N. Korotkov, "Coulomb Blockade and Digital Single-electron Devices", in: *Molecular Electronics*, edited by J. Jortner and M. Ratner (Blackwell, Oxford, 1997), pp. 157-189.

23. K.K. Likharev, "Single-Electron Devices and Their Applications", to be published in a special issue of Proc. IEEE on Nanoscale Devices (January 1999).